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Low Power on-the-Ground Tests**

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**THE NASA B-757 HIRF TEST SERIES
- LOW POWER ON-THE-GROUND TESTS -**

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ABSTRACT

The data acquisition phase of a program intended to provide data for the validation of computational, analytical and experimental techniques for the assessment of electromagnetic effects in commercial transports, for the checkout of instrumentation for following test programs, and for the support of protection engineering of airborne systems has been completed. Funded by the NASA Fly-By-Light/Power-By-Wire Program, the initial phase involved on-the-ground electromagnetic measurements using the NASA Boeing 757 and was executed in the LESLI Facility at the USAF Phillips Laboratory. The major participants were LLNL, NASA Langley Research Center, Phillips Laboratory, and UIE, Inc. Measurements were made of the fields coupled into the aircraft interior and signals induced in select structures and equipment under controlled illumination by RF fields. A characterization of the ground was also performed to permit ground effects to be included in forthcoming validation exercises. A series of fly-by experiments were conducted in early 1995 in which the NASA B-757 was flown in the vicinity of a Voice of America station (~25 MHz), a fixed transmitter driving an LP array (172 MHz), and an ASRF radar at Wallops Island (430 MHz).

In this paper, the overall test program is defined with particular attention to the on-the-ground portion. The test rationale, test layout, and samples of the data are described. Samples of some inferences from the data that will be useful in protection engineering and EM effects mitigation will also be presented.

INTRODUCTION

The NASA Fly-by-Light / Power-by-Wire (FBL/PBW) program was initiated to develop technology for a future generation of commercial transport aircraft. An all-electric aircraft (PBW) could have substantial benefits in terms of weight and maintenance costs over aircraft that rely on hydraulic and pneumatic controls. However, a major concern of such an architecture is the potential for conducted and radiated electromagnetic susceptibility of its electronic controls. A way to potentially alleviate this problem (and save weight at the same time) is to route all control and signal information over

optical fiber control links (FBL) that are inherently easier to harden against the electromagnetic environment (EME).

Since electro-optic devices and electronic digital computers will still be required, a major objective of the FBL/PBW program is to develop and refine tools and techniques for assessing the survivability of the modern aircraft using such equipment in the electromagnetic environment that includes both externally generated high intensity radiated fields (HIRF) and internally-generated radiated or conducted emissions.

The EME effects assessment tools and techniques must ultimately be accepted by industry and the FAA regulatory body to be useful. Therefore, an important aspect of the program is to validate these tools and techniques to the satisfaction of this community. A series of aircraft tests, specifically, low power on-the-ground tests at frequencies up to 1 GHz and fly-by tests using three RF radiators in the HF, VHF and UHF ranges, have been conducted under NASA Langley Research Center sponsorship. This paper describes the on-the-ground tests, which include those used for generating data for code validation as well as those which might support the development of protection engineering guidelines. Details of the experiments are included in a comprehensive test plan that was prepared prior to test execution [1]. The fly-by test data is presently being processed by NASA LaRC.

OBJECTIVES

The NASA B-757 HIRF Test Series

The primary thrust of this aircraft test program, both on-the-ground and fly-by, is to develop a library or database of experimental results that were obtained using techniques as close to the "scientific method" as possible. This data could then be used for the validation of computational, analytical and experimental techniques for the assessment of electromagnetic effects in commercial transports and for the support of protection engineering of airborne systems. The on-the-ground tests were also to provide a checkout of instrumentation for following test programs.

The primary test object is a Boeing 757-200 owned by NASA. The onboard certificate identifies it as a 757-225 with the 225

denoting a configuration requested by the original sole owner, Eastern Airlines.

Aircraft flight tests are required to convince the community of the validity of effects assessment techniques for in-flight aircraft. However, such tests are difficult and expensive. Orientation and position parameters and incident wavefront parameters are difficult to control or measure accurately in such a test. A series of on-the-ground tests was planned and executed to validate both modeling and mode-stirred measurement techniques under well-controlled conditions. These tests generated a wealth of data of significant value to the technical community. They were carried out prior to the flight tests to provide data under better controlled conditions and to reduce the risks associated with the flight tests.

The fly-by tests included measurements from fixed frequency sources capable of illuminating the aircraft in flight with fields of sufficient magnitude to generate measurable signals at select test points within the aircraft. These tests used RF radiation from a UHF radar at Wallops Island (430 MHz), an LP antenna driven by a VHF source (172 MHz), and a VOA station in Greenville, NC (25.8 MHz).

THE ON-THE-GROUND TEST SERIES

On-the-Ground Test Objectives

There were four objectives and four test series for the on-the-ground tests. The first test series was meant to generate data for the library which will be used directly for coupling code validation. For this objective, discrepancies and uncertainties between measurement and model were to be minimized or at least understood and quantized. These tests used dipole antennas, so the antenna can be included in the model, thus eliminating the uncertainty in the exact form of the wave entering the problem space.

The second test series was meant to exercise the equipment that would be used for the fly-by tests. For these tests, the test signals were expected to be a reasonable match to those planned for the fly-by tests.

The third test series was meant to prepare for the fly-by tests, as well as to provide more data for validation of the codes and for the development of protection engineering guidelines. These measurements investigated the coupling into the airframe so that resonances near the fly-by frequencies could be taken into account as could the sensitivity of coupling to uncertainties in aspect angle or the position of interior objects. The fourth test series involved a continuing study of stirred frequency techniques.

The first and third test series are the primary subject of this paper. The fly-by test equipment check and the stirred frequency or statistical electromagnetics tests are not described in this paper.

On-the-Ground Test Facility

The tests were conducted at the US Air Force Phillips Laboratory (PL) Large Electromagnetic System-Level Illuminator (LESLI) test facility. This facility, shown in Figure 1, consists of a concrete pad, a two-wire rhombic antenna with suitable terminating loads to minimize reflections at the termination, a source shack with sources and RF amplifiers, and an instrumentation trailer.

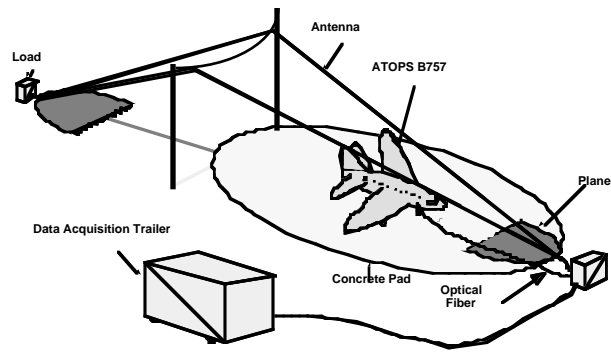


Figure 1. Sketch of LESLI facility with rhombic

Figures 2 and 3 are scaled views of the LESLI pad and one-half of the rhombic. The B-757 is shown in both configurations (nose on and broadside) in Figure 2. The aircraft location was chosen as a tradeoff between available illuminating field strength and the uniformity of illumination over the portion of the aircraft expected to be a dominant contributor to HIRF coupling to

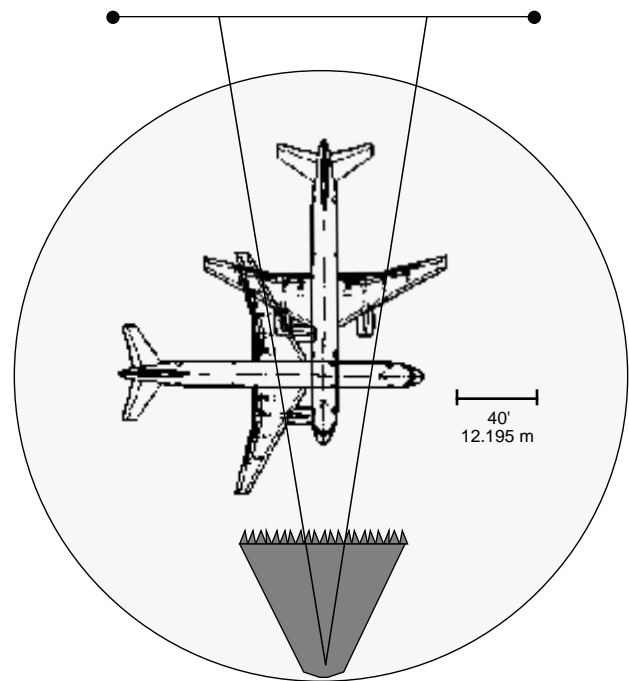


Figure 2. B 757 in LESLI with nose on and broadside orientations superimposed

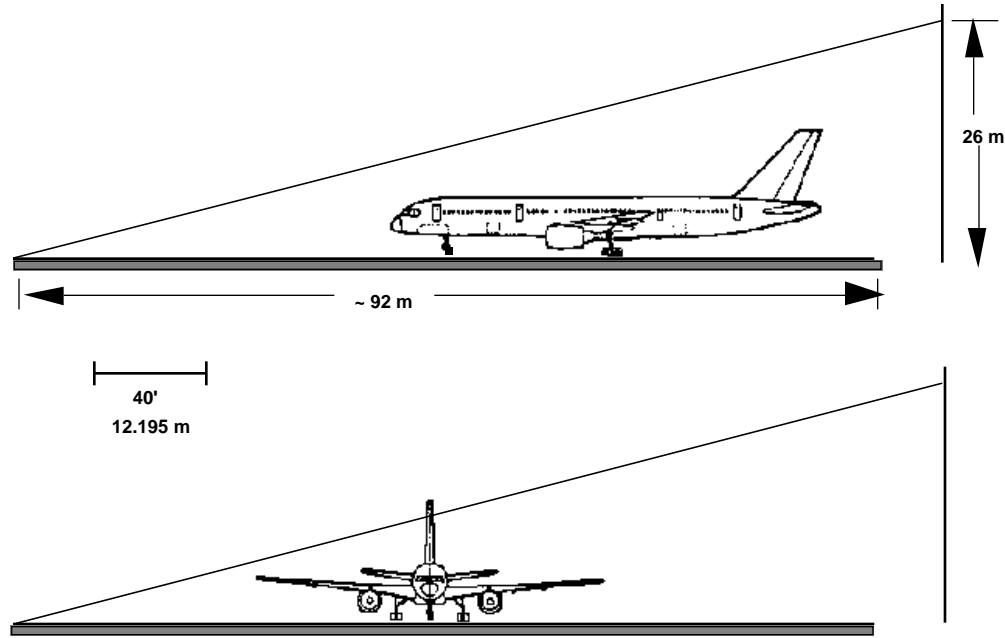


Figure 3. Side view of LESLI with B 757

interior test points to be defined in a following section. The aluminum transition region (the triangular shape near the feedpoint), allows the feedpoint for the rhombic to be located over a highly conducting ground section. The concrete surface forming the pad in the LESLI facility will be used in an unaltered state as the ground surface. The characterization of this material will be discussed later.

Sensors

A suite of 12 sensors sampled fields, cable currents, and voltages in three aircraft bays: the cockpit, the electronics bay, and the cabin.

There were five sensors in the cockpit (Figure 4) all of which were mounted on a sensor box referred to as the ATOPS box. The box contained three orthogonal D-dot sensors and a wire that extended through the box on which a voltage measurement was made within the box. In addition, a current probe was used on the bare wire just outside of the box.

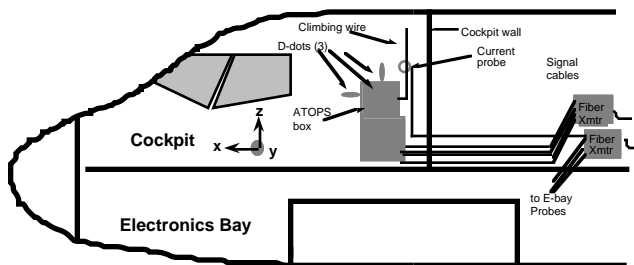


Figure 4. Cockpit Sensors

The electronics bay contained three sensors as shown in Figure 5. A D-dot probe was used to measure fields within the bay. A current probe was placed on an existing aircraft line for the windshield heater within the bay. A third measurement in the electronics bay was made in an unpowered Collins VHF-700 transceiver box which had been previously modified to provide a probe to measure the voltage on an internal power line pin and which was installed into an existing slot in the electronics rack in the electronics bay. The box was thus connected to the avionics bus for low RF power stepped frequency tests.

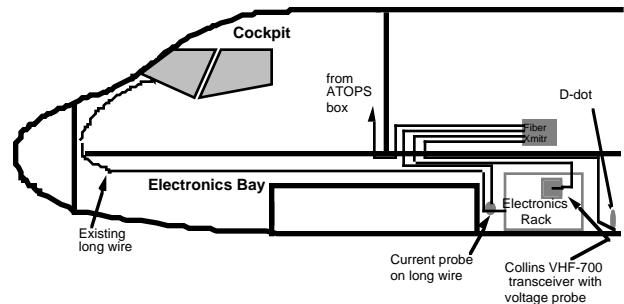


Figure 5. Electronics Bay Sensors

Four sensors were located in the cabin area as shown in Figure 6. One of these was a D-dot mounted on top of the EME instrumentation rack. The second sensor was a long wire mounted along the ceiling of the cabin which allowed the measurement of small-signal low-frequency coupling and which was terminated in a 50 ohm cable across which voltage was measured. A current sensor was also installed onto the semi-rigid coaxial cable feeding the long wire to sense external shield current. The fourth cabin sensor was the VHF-L (left) antenna

which is part of the normal complement of external antennas for the NASA aircraft. This antenna would provide a measurement of the external field (perturbed by the aircraft) and a strong signal to be used as a trigger for the fly-by tests.

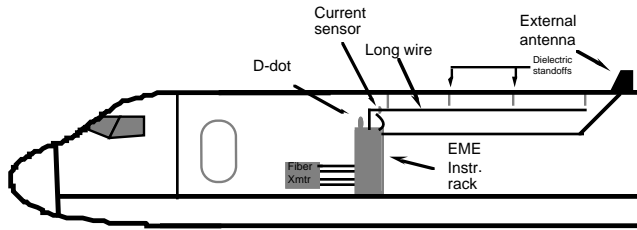


Figure 6. Cabin Sensors

Data Acquisition, Processing and Analysis

CW data acquisition was accomplished using the CWDAS hardware and software configured in a two-network analyzer setup. Figure 7 shows the acquisition setup and data processing flow with the radiator referring to either a dipole or rhombic element. Each test point is connected by coaxial cable to a fiber optic transmitter that communicates via optical fiber to a fiber optic receiver in the source shack. The outputs of these receivers are connected to a recording channel on an HP 8753C Network Analyzer. The amplifiers lead to a driving power in the 100 watt range.

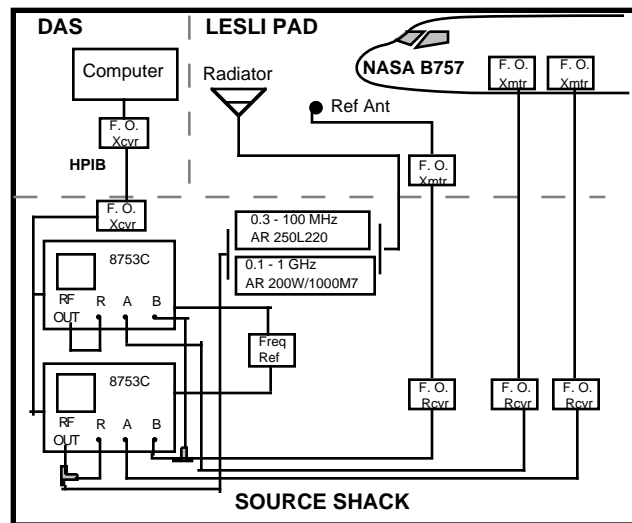


Figure 7. Test Instrumentation

The output data from the network analyzers are ultimately brought to another computer where they are processed to introduce probe and cable calibration factors so that data acquisition system effects can be unfolded from the "raw" data.

Dipole Antenna Tests

Dipole antennas were used as radiators for this test series. For validation studies, the dipole radiator can simply be included in

the model. Also, it is very well understood as a source of illuminating fields and has been accepted in the technical community for code validation studies. The antennas were simple thin-cylinder or thin-wire antennas mounted parallel to both the aircraft fuselage axis and ground for horizontal polarization or mounted perpendicular to the ground for vertical polarization. The geometrical arrangement is shown in Figure 8 with all coordinates in meters and the origin at the nose of the aircraft, as shown. The dipole source (its center) was located at $(-4, 3, -5)$ for all frequencies except for the vertical polarization test near 25.85 MHz when the center was raised to $(-4, 4, -5)$. A reference probe (B dot sensor) was used in the measurements and was located 3.5 meters from the dipole source for all frequencies except for the measurements near 25.85 MHz when the sensor was 5 meters from the dipole source. The coordinates for the reference were $(-1.525, 3, -7.475)$ and $(-0.465, 3, -8.535)$, respectively.

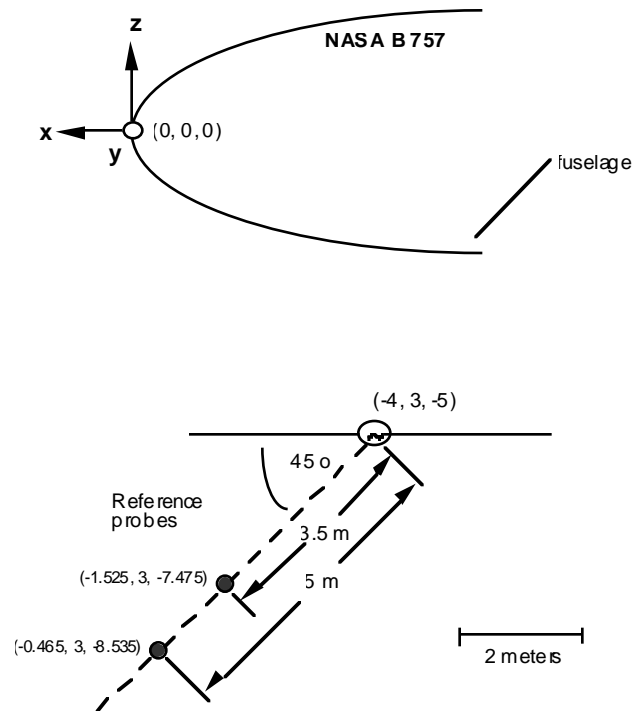


Figure 8. Dipole and reference probe location

The dipole antennas do not have ultra-wide bandwidths so that separate antennas were required for each of the three fly-by frequencies, namely, 25.850 MHz, 172.0 MHz, and 430 MHz. The dipoles were cut to half-wavelength resonance near each fly-by frequency and stepped frequency measurements were made over a band extending from 80% to 120% of each center frequency or as permitted by equipment VSWR restrictions. The aircraft was illuminated with both vertical and horizontal polarization using dipoles for both polarizations.

Some limited field mapping for the dipole antennas was also carried out. Eighty four tests were executed during the dipole test sequence. Initial tests included dynamic range and noise

floor measurements. Then frequency was stepped over a range around three center frequencies for two polarizations. The ranges were 23-28 MHz, 150-200 MHz, and 350-500 MHz. Measurements were made with the twelve sensors.

The dipole tests did not uncover any strange behavior of the radiating system nor any “interesting” phenomenology. But, the results were of “validation” quality and will serve that purpose very effectively.

Not surprisingly, the 172 MHz signals due to V polarization coupled to the interior of the aircraft more effectively than 25 MHz signals. In the cabin, this was observed to be as much as a factor of 8 measured with a vertical field probe and the horizontal long wire. For horizontal polarization, the cockpit fields were about twice as high as the cabin fields.

LESLI Rhombic Illuminator Tests

The rhombic illuminator in the LESLI facility has a number of attractive features that supported its use in these ground tests. The rhombic has reasonably uniform fields in a working or modeling volume. The field within the illuminators working volume is characterizable using either simple approximations such as transmission line models or full wave numerical solutions for the fields in the frequency or time domain. Of course, the transmission line model is an approximation which is not adequate for validation studies but can be used effectively for field estimation. Additional attractive features were that the facility was adjacent to a suitable runway, was well understood by PL staff, had been widely used in other aircraft studies, and was able to cover the desired frequency range from 0.3 MHz to 1 GHz. The bound wave nature of the facility and the frequency clearances already in effect made the operational utilization of the facility straightforward.

The majority of the tests were performed with the rhombic illuminator in the common mode drive configuration, i. e. , with each arm of the rhombic driven against the aluminum ground plane. This gave rise to a dominant vertically polarized field in the test volume. The lack of availability of a high quality, high power, broadband balun capable of operation over 0.3 MHz - 1 GHz prevented the differential mode configuration and horizontal polarization. Nonetheless, limited horizontal polarization test were conducted in the 3 - 30 MHz range using a balun available in the amateur radio community. Some sample results are presented later.

Typical LESLI Rhombic Results

Given the expected field characteristics, the rhombic illuminator lent itself well to a number of studies. First, a limited field mapping was performed to provide a set of data that could be used in the future to validate the ability to predict the fields everywhere in the simulator in the absence of the airplane - the incident field.

The actual test program involved (not necessarily in this order) measurement of the signals at the twelve test points in Figures 4 to 6 for both nose-on and broadside incidence (Figure 2). Then questions regarding sensitivity of the signals to various variables were addressed. The 757 was rotated 10° from nose on to assess the effect of such angular displacement on the coupled signals. Given the small variation encountered, less than 2 dB, tests for smaller angles were eliminated. Then a small metallic box (of typical “resolution cell size” in the vernacular of finite difference and finite element modelers) was introduced near the ATOPS box and moved around. This was meant to shed some light on the effects of “small” objects on the results and possibly lending credibility to ignoring them in the models.

The effects of the presence of humanoids in the cockpit and cabin as well as their location was investigated to assess whether they were critical factors in establishing field levels. The tests included no presence, a filled right seat, both seats occupied in the cockpit, and personnel movement in the cabin.

It was noted that the external hatch cover for the electronics bay did not have a continuous electrical seal but rather had a rubber seal with only intermittent electrical contact. At nose-on incidence, the results for the hatch closed (covered) were augmented with tests of cases where the hatch was completely open (uncovered) and where the hatch was sealed (taped) with conducting tape. Typical results for the vertical electric field in the E bay are shown in Figure 9. The results above 100 MHz are being studied.

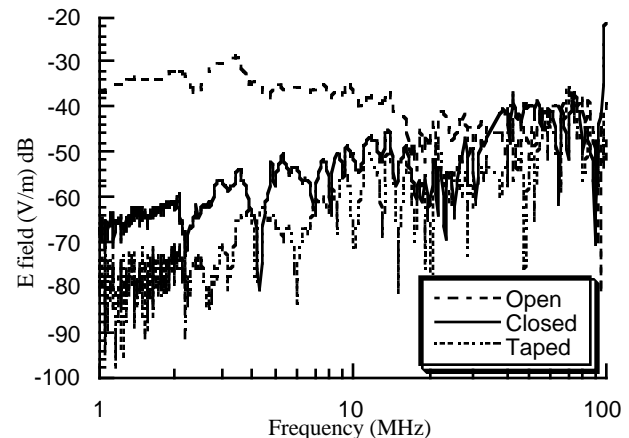


Figure 9. Vertical E bay electric field for different hatch cover states

It has been speculated that the windshield in commercial transports is a major port of entry for electromagnetic radiation. To test this conjecture, the nose-on tests for selected test points were repeated with the windows in the cockpit completely covered with metallic foil that is bonded to the metallic fuselage with conducting tape. Significant differences were quite apparent and typical results for the vertically oriented field at the ATOPS box in the cockpit are shown in Figure 10. Differences of approximately 20 dB are not uncommon.

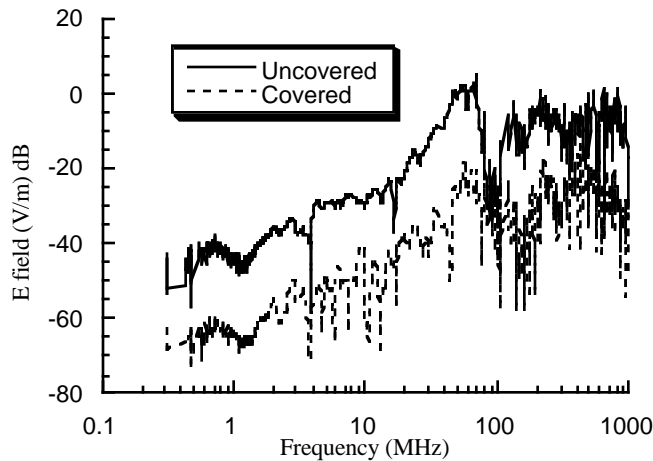


Figure 10. Vertical electric field in cockpit with windows covered and uncovered

The details of electrical system configuration can have a significant effect and yet are often overlooked. The impact of opening and closing a single circuit breaker on the vertical E field in the electronics bay was considered. As seen in Figure 11, the impact on the vertical E field is not insignificant in the 1 to 100 MHz range. The results above 100 MHz are being studied.

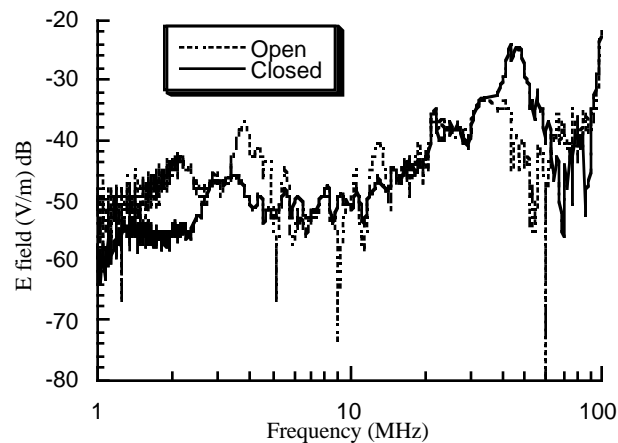


Figure 11. Vertical electric field in E bay for two states of a single circuit breaker

The repeatability of the measurements (execute the same test series at different times after airplane movement or measurement system changes) was also investigated to assure the robustness of the results. The effects of a static ground were even looked at for completeness.

The LESLI Pad Characterization

As has already been mentioned, the constitutive parameters of the concrete pad had to be measured to permit modelers to include the ground characteristics in simulations. Furthermore, since the concrete/rebar/soil was neither precisely describable

nor homogeneous, a measurement scheme returning parameters averaged over a spatial extent was required. Operational restrictions mandated a noninvasive measurement scheme.

To execute the tests, a long wire (the rhombic wire) was supported a fixed height (less than one inch) above the concrete pad on a Styrofoam support strip and was extended across the pad to the full extent of the wire. The height was chosen to be as small as possible. The wire was driven against the aluminum source-region ground screen at the rhombic feed point and the current distribution was measured. This permitted estimates of the attenuation and phase constants of the wave propagating along the wire. From this information, the conductivity and permittivity of the pad were extracted using the theory presented by Chang, Olsen and Kuester. The details, including references, are reported in [2]. Basically, the inverse problem was solved - given the current measured on the infinitely long wire closely coupled to the ground, determine the constitutive parameters that are consistent with the results.

CONCLUSIONS

The NASA-supported B-757 HIRF Test Series pertaining to on-the-ground and fly-by tests has been successfully completed. Data analysis is presently ongoing. In this paper, elements of the on-the-ground tests were described and sample results provided. The data are of such quality as to provide a high quality library enabling code validation to be performed. Dipole radiator tests were particularly well suited to this task. Rhombic illuminator tests augment the database. The data were acquired in well thought out experiments to provide validation data as well as to uncover phenomenology. Many tests under rhombic illumination were conducted to study such items and to provide some guidance for protection engineering.

ACKNOWLEDGMENT

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